Études océan Indien

46-47 (2011)
Vohémar, cité-État malgache

Frank Preusser et Guido Schreurs

Dating sediments in coastal areas and potential applications for constraining the palaeo-environmental context of an archaeological site at Vohemar

Référence électronique
Frank Preusser et Guido Schreurs, « Dating sediments in coastal areas and potential applications for constraining the palaeo-environmental context of an archaeological site at Vohemar », *Études océan Indien* [En ligne], 46-47 | 2011, mis en ligne le 03 mars 2013, consulté le 15 juillet 2016. URL : http://oceanindien.revues.org/1344 ; DOI : 10.4000/oceanindien.1344

Éditeur : INALCO
http://oceanindien.revues.org
http://www.revues.org

Document accessible en ligne sur :
http://oceanindien.revues.org/1344
Document généré automatiquement le 15 juillet 2016. La pagination ne correspond pas à la pagination de l'édition papier.

Frank Preusser et Guido Schreurs

Dating sediments in coastal areas and potential applications for constraining the palaeo-environmental context of an archaeological site at Vohemar

Pagination de l'édition papier : p. 339-355

1 Coastal settings represent complex environments in the transition between ocean and land. From the geological perspective, coasts are highly dynamic areas with short frequency but low amplitude changes caused by daily low and high tides, and occasional storm events partially having a high impact on geomorphology. Long term trends are due to raising or decreasing sea level caused by global climate change, and emerging or sinking coast lines due to tectonic movements. Climate change also affects the frequency and magnitude of severe storm events (*e.g.* during the "Little Ice Age") and triggers changes in the vegetation cover in coastal areas (*i.e.* the effectiveness of sediment trapping). Additionally, seismic events, often occurring thousands of kilometres away, may cause substantial modification of coastal areas. This was recently dramatically demonstrated by the devastating tsunamis in the Indian Ocean in 2004 and off the eastern coast of Japan in 2011.

2 A traditional method to date past changes in coastal environments is the analysis of historical maps and aerial images. Examples are available from the southern Baltic Sea (*e.g.* Schwarzer *et al.* 2003) and the Netherlands (*e.g.* van Heteren *et al.* 2006). The problem is that these approaches only cover the last few centuries and that not all regions have been mapped in detail in the historic past. As a consequence, it is often necessary to rely on physical dating methods that, however, are restricted to certain time scales and materials.

3 This article provides a brief overview of the most common geochronological methods used for dating deposits from coastal settings of Holocene age. We will first give a short description of the basics of the physical dating methods followed by examples of how these have been applied to different sedimentary environments. Specific focus will be on Optically Stimulated Luminescence (OSL) dating, a method that has recently seen a number of innovative applications for reconstructing the environmental history in coastal settings. We also show that the presented dating methods, in particular OSL dating of sediments, could be extremely useful in palaeo-environmental studies of an archaeological site at Vohemar in north eastern Madagascar in order to decipher the history of past changes induced by natural processes and human settlement.

Dating methods

Radiocarbon

4 Radiocarbon is the most commonly used dating method in geosciences and archaeology. The method relies on the decay of ^{14}C produced in the atmosphere by cosmic radiation, mixed throughout the global circulation system, and finally incorporated in organic material or carbonate precipitates, for example in corals. The method is well established, very precise and several laboratories offer dating on a commercial basis. However, a major problem of radiocarbon dating is that it is restricted to organic matter, which is seldom or even absent in many sand-dominated coastal areas. A further disadvantage of this approach is that the dated material might be reworked and, hence, in some settings may not necessarily date the time of sediment deposition. Radiocarbon ages of reworked material may hence significantly pre-date the event represented by a sediment layer it has been taken from. Another drawback is that radiocarbon can be affected by the marine reservoir effect, which will also cause age

overestimation. Furthermore, the calibration of young radiocarbon ages is partially associated with large uncertainties. For example, a radiocarbon age of 150 ± 40 ^{14}C yr BP encompasses five different possible age ranges between AD 1660 to 1950 after calibration (Hua 2009). A comprehensive overview of the radiocarbon methods is provided by Hajdas (2008).

Uranium series

5 Uranium with its several radioactive isotopes occurs in small concentrations in most natural environments. The isotope ^{238}U represents the starting point (mother isotope) of a complex decay chain, finalising in stable ^{206}Pb. In contrast to its daughter isotopes, uranium is highly soluble in water. When organisms such as corals trigger precipitation of carbonates from seawater to build their exoskeleton, these precipitates will contain U, but no decay products such as ^{230}Th. At this starting point the U/^{230}Th ratio is zero but will increase as soon as ^{230}Th is produced by the decay of U. Knowing the decay rate of U allows calculating an age based on the ratio U/^{230}Th. While the method was originally developed in the 1950s, it has seen major improvements with regard to accuracy and precision during the last 20 years due to developments in analytical methods. Problems occur when the system is not closed, *i.e.* when uranium or thorium is added or can escape from the system. In the present context, this can occur when corals are exposed to weathering. A summary of uranium series dating is given in Scholz and Hoffmann (2008).

Optically stimulated luminescence (OSL)

6 This method relies on a light-sensitive signal in quartz and feldspar sediment grains that is induced by environmental radioactivity. When the grains are exposed to daylight during sediment transport, the OSL signal is erased within minutes to hours. During burial, when the grains are sealed from daylight, the latent OSL signal accumulates as a function of time and environmental dose rate. For purposes of dating two measurements are necessary. One has to determine the amount of radioactive elements (*i.e.*, K, Th, U and their daughter isotopes) and this is done by, for example, gamma spectrometry. Additionally, parameters such as water content, sediment overburden, and geographic position have an effect on dose rate calculation. The second measurement quantifies the amount of radioactive energy absorbed by the minerals by comparing the natural OSL signal in a sample to the OSL signal produced by known dose laboratory irradiation. One advantage of OSL is that the method relies on quartz and feldspar grains, both of which are found in most coastal sediments. The method does not, in contrast to radiocarbon and uranium series dating, require the presence of organic material and it provides direct depositional ages (last exposure to daylight) for a variety of different coastal features (beaches, dunes, tidal sequences, storm deposits, etc.). Furthermore, the datable time range reaches from a few years up to several hundred thousand years. However, the methodology is rather complex and requires extensive testing and data analyses. The basic concepts and procedures of OSL dating are summarised in Preusser *et al.* (2008).

Sedimentary settings and dating approaches

Coral reefs

7 In tropical oceans, corals commonly build up large structures by precipitating CO_2 from water. An important function of coral reefs is that they act as natural barrier towards the open sea, hence protecting the coast from the effects of storms. Besides being an important habitat for present sea life, corals also provide important information about changes in past environmental conditions (*e.g.*, Fleitmann *et al.* 2007).

8 The fact that corals are build up by precipitated carbonate allows the application of radiocarbon dating. A problem with this approach is the so-called marine reservoir effect, *i.e.* the CO_2 precipitated from ocean water will have aged due to the time it takes for mixing. As a consequence, marine organisms show usually over-estimated radiocarbon ages in the order of several centuries up to several thousand years (*cf.* Hajdas 2008).

9 A recent innovative application of Uranium series dating used laser ablation multi-collector inductively coupled plasma mass spectrometry (LA MC-ICPMS) to determine the approximate age of fossil corals (Potter *et al.* 2005, McGregor *et al.* 2011). LA MC-ICPMS is a rapid (40-50 samples per day) and inexpensive analytical method to optimise selection of quality coral material belonging to a required age range. In the study by McGregor *et al.* (2011), the LA MC-ICPMS ages of the investigated corals ranged between 6400 and 900 years, and are generally constrained by solution uranium series and radiocarbon dating. However, for particular samples laser ablation gave results conflicting with solution MC-ICPMS, implying the method may not always able to detect subtle geochemical alteration.

Tidal zone deposits

10 Tidal zones are areas strongly affected by daily movement of the coastline due to low and high tide. In such environments large bodies of sediment are accumulated from the supply by rivers and marine currents. Especially deltas and estuaries can strongly modify tidal zones due to the large input of sediment. The sorting of particle sizes causes a zonation into sand flats, mixed flats and mud flats. Sorting is controlled by several factors such as velocity of tidal waves and water depth, resulting in different bed forms.

11 A typical example of a tidal flat is the coast along the North Sea, where several pilot studies have tested the potential of Osl dating. Pioneering work was by Madsen *et al.* (2005, 2007a, 2007b) who showed for most of their samples a satisfactory consistency between Osl and ^{210}Pb ages even for estuarine samples as young as a few years. On the other hand, Mauz and Bungenstock (2007) and Mauz *et al.* (2010) found that not all their Osl ages for samples taken from different sedimentary settings on tidal flats are well bleached and partially result in age overestimation. However, it is emphasized that using small aliquot or single grain procedures together with appropriate statistical analyses of large data sets might overcome this problem. In this approach, partial bleaching is identified by the spread of the results of repeated Osl measurements, where the real deposition age is at the lower edge of the distribution. Another problem in such environments can be the presence of radioactive disequilibrium in the uranium decay chain, caused by the presence of shell debris (Zander *et al.* 2007). Detection and quantification of such disequilibria is possible through the application of high-resolution gamma spectrometry. Modelling the effect of disequilibrium on Osl ages is not straightforward, as the system may have acted differently (*e.g.*, closed system or post-depositional up-take of Uranium). Zander *et al.* (2007) compared different models and found good consistency of their Osl with age control provided by radiocarbon dating of wood, indicating that modelling disequilibria might help to minimise the effect on age determination.

Shoreline deposits

12 Shorelines, also termed beaches, comprise several parts, which relate to the processes shaping them. The part above the waterline that is actively influenced by the action of waves is termed beach berm. It consists of a crest and face sloping down towards the ocean. Sediment is in this environment continuously reworked by wave action. Older crests further inland beyond the range of normal waves result from storm events (storm beach). Both waves and currents move sediment particles towards the beach causing accumulation, whereas erosion along beaches is often related to storm events. Winds acting on beaches often force the movement of sand-size grains inland resulting in the deposition of dune ridges along the coast. Such dune belts represent natural dykes protecting the coastal hinterland from flooding. As these features have a high preservation potential, they are used to reconstruct changes of past shoreline positions. Dune sand is probably the material best suited for OSL dating as aeolian transport almost guarantees complete resetting of the signal prior to deposits. Furthermore, dune sands are usually highly homogenous and less commonly affected by problems of radioactive disequilibrium than met in other coastal setting.

13 Beach ridges along the Baltic Sea coast in Germany were dated by Reimann *et al.* (2010) using OSL. It is shown that beach ridges on Darss-Zingst were formed between 1900 and 1600 years ago, before the closing of coastal inlets. Accumulation at Windwatt occurred during

four distinct periods, dating to ca. 900, ca. 500, 320-260, and ca. 40 years ago. The authors assume,that deposition 500 years ago (AD 1500) and between 320 and 260 years ago (AD 1680-1750) was related to the mobilisation of sediment caused by environmental change during the onset of the "Little Ice Age". The youngest phase of sediment accumulation could be caused by storm surges and sediment overwash during the 1960s.

14 A case study by Ballarini *et al.* (2003) has dated young dune systems from the SW part of the Dutch island of Texel. These authors produced ages as young a 6 ± 2 years, with ages between 100 and 300 years being associated by uncertainties of about 7%. The reported dune chronology is in excellent agreement with age control provided by historic maps showing the development of the dune system. Clemmensen *et al.* (2009) reconstructed the history of coastal dune fields on Jutland (Denmark) using both OSL (on aeolian sand) and radiocarbon (on intercalated peat). It is shown that the development of the dune field was characterised by repeated periods of transgressive dune formation punctuated by periods of dune stabilization and soil formation. Aeolian activity is dated to 2200 BC, 800 BC, 100 AD, 1050-1200 AD and 1550-1650 AD. Proxy data from other geological archives in the region indicate that aeolian deposition coincides with increased storminess during summer.

Coastal flats

15 Many coasts are characterised by areas of low topography located in the upper intertidal zone, at the transition between land and salt or brackish water. Coastal flats are often protected from the open sea by barrier islands, spits or embankments. In the mid to high latitudes such areas are known as salt marshes, being characterised by dense low vegetation (*i.e.* grass and shrubs) of salt tolerant plants. In tropical and sub-tropical environments mangroves are found in such positions, where salt tolerant trees replace herbaceous plants. A special feature along coastal flats are lagoons, bodies of shallow salt or brackish water separated from the open sea by sand barriers (*e.g.*, barrier islands) or coral reefs, where such areas are also known as back reef.

16 Szkornik *et al.* (2008) mapped the extent of an aeolian sand sheet accumulation in the salt marshes of Ho Bugt, Denmark, from c. 60 cores and sections, and dated it using a combination of radiocarbon (plant fragments) and Osl (aeolian sand). Diatom analysis was used to reconstruct relative changes in sea level during the late Holocene. It is shown that the relative sea level in Ho Bugt has risen by approximately 1.5 m in the past 2000 years. Higher than average sea level rise occurred during two periods, the first dating between 2000 and 1400 years ago. The second started about 500 years ago during the early part of the "Little Ice Age". Deposition of the sand sheet dates to the 15th and 16th century, and coincides with increased storminess, coastal dune building, and salt marsh formation observed at other coastlines in Europe at that time. Another study from Denmark focussed on the environmental evolution of the past 5500 years of the coastal lagoon behind the barrier island of Fanø, in the Northern Wadden Sea (Fruergaard *et al.* 2011). Sedimentation in the lagoon alternated between slow vertical aggradation of sand flats and fast lateral progradation of point bars in tidal channels. The authors conclude that sediment accumulation on millennial time scales was controlled by rising sea level. Short-term sediment accumulation (centurial time scale) was controlled by local erosion and deposition caused by the migration of channels.

Storm and tsunami deposits

17 Exceptional events may occur at low frequency but can partially have a dramatic impact and by this substantially changing the appearance of coastlines. Large storm events (hurricanes, taifuns) as well as tsunamis can cause major erosion and transport of large sediment particles inland. In the geological record, tsunamis gained very little attention in the past and have only recently moved into the focus of geological research (*e.g.*, Chagué-Goff *et al.* 2011). Morton *et al.* (2007) investigated modern tsunami and storm deposits to distinguish such sediments in the geological record. According to these authors, diagnostic criteria include sediment composition, textures and grading, types and organisation of stratification, thickness, geometry, and landscape conformity. The distinction between tsunami and storm deposits is based on differences in hydrodynamics and sediment-sorting process during transport. Tsunamis can have flow depths of >10 m, transport sediment primarily in suspension, and

distribute the load over a broad region where sediment falls out of suspension when flow decelerates. In contrast, storm inundation generally is gradual and prolonged, consisting of many waves that erode beaches and dunes with no significant overland return flow until after the main flooding. In the geological record, tsunami deposits will usually consist of a single homogeneous bed that is normally graded overall. Mud intraclasts and mud laminae within the deposit as well as twig orientation or other indicators of return flow during bed aggradation are interpreted as strong evidence of tsunami deposition. On the other hand, storm deposits are usually thicker and found less inland from the shore. They typically are composed of numerous subhorizontal planar laminae, do not contain internal mud laminae, and rarely contain mud intraclasts.

18 One of the first studies dating storminess by OSL was by Sommerville *et al.* (2003) on samples from Scotland. More recently, Buynevich *et al.* (2007) reconstructed the dynamics of coastal storm events by OSL dating of sand filling up relict scarps produced by past storm events in the western Gulf of Maine, USA. These results indicate severe beach erosion occurring ca. 1550, 390, 290, and 150 years ago. From this, the authors infer increased storm activity (frequency and/or intensity) during the past 500 years, which preceded a relatively calm period lasing some 1000 years.

19 Several studies have tested radiocarbon and Osl dating on deposits attributed to the great tsunami that hit the coast of Portugal on November 1st, 1755. An eyewitness reported an estimated run-up of 11-15 m and historical records indicate flooding of the coastal wetlands up to 1 km inland. The tsunami-laid material consists of sand and gravel intercalated with estuarine mud. It contains shell fragments, cobbles and boulders with borings by marine organisms. Radiocarbon ages of embedded organic material are often predating the tsunami, as they have been reworked (Dawson *et al*. 1995). Cunha *et al.* (2010) report Osl ages for the tsunami deposits being internally reproducible, but overestimating the known age by some 60-310 years. Similar age overestimation has been reported for deposits of the 2004 tsunami (Murari *et al.* 2007). The age overestimation is interpreted to result from incomplete bleaching of the Osl signal prior to deposition. In this context, it is important to note that the age offset will become less significant when dating older (> a few thousand years) deposits. Furthermore, the use of single grain methodology and application of minimum age models may help to reduce or even avoid age overestimation caused by incomplete bleaching.

The archaeological site at Vohemar in a palaeo-environmental context

The archaeological site at Vohemar

20 Excavations at a necropolis in Vohemar during the first half of the 20th century have provided evidence for the presence of a former prosperous civilisation referred to as the Rasikajy civilisation (Vernier & Gaudebout 1941). The necropolis is located on a peninsula a few hundred meters from the Indian Ocean (fig. 1). Until now remains of a former settlement that most likely was situated nearby have not been discovered. Previous studies indicate that the necropolis existed prior to the arrival of the first Europeans in 1500 AD (*e.g.* Vernier & Millot 1971). The presence of early 16th century Chinese ceramics (Crick, pers. comm.) and Spanish pottery (Rosser-Owen, pers. comm.) in the tombs indicates that the cemetery was still in use during the first half of the 16th century. This is confirmed by historical sources, which mention that a Portuguese ship traded at Vohemar in 1514 or 1515 (Barros 1777). Inhumations at the cemetery seem to have ceased later in the 16th century, as there is no clear evidence for burial objects dating from the 17th century or younger. The reason for the abandonment is not known, but descriptions of Madagascar compiled in the late 16th (Thevet 1575) and early 17th century (Megiser 1609) mention destructive flooding events affecting coastal regions of Madagascar. The Frenchman Mayeur, who travelled extensively on foot throughout northern Madagascar in the 1770s, also visited Vohemar and his travel notes mention that the local population informed him that the port of Vohemar had been destroyed in the past by a cyclone and that the settlement had subsequently been abandoned (de Froberville 1912).

Palaeo-environmental studies in the Vohemar region: an outlook

21 A study of the nature and extent of sedimentary deposits at or near the necropolis of Vohemar could shed light on whether natural hazards (*e.g.*, tsunami, storm surges associated with cyclones, or river floods) played a role in the demise of the Rasikajy civilization. In addition, palaeo-environmental studies at Vohemar and other selected archaeological sites in northern Madagascar could provide insights on how the natural environmental conditions influenced coastal sites in the past and how the landscape developed under human activity and changing climatic conditions. The timing of palaeo-environmental events and changes needs to be constrained by dating methods such as those presented in this article.

22 Palaeo-environmental studies of the Vohemar region will need to comprise geomorphological, sedimentological, micromorphological and geochemical studies in order to clarify depositional processes in a coastal setting. Wherever possible, deposits are best dated by a combined approach of radiocarbon, OSL, uranium series and archaeological age determinations. OSL dating is particularly promising in the coastal setting at Vohemar as suitable material (sand or silt-sized grains of quartz and feldspar) is available ubiquitously in most environments.

Landsat ETM+ satellite image of the Vohemar region

Bands 3, 2 and 1 = red, green and blue; converted in gray scale.
Black circle indicates location of necropolis.
Numbers are potential sites for palaeo-environmental studiesand are referred to in the text.

23 Examples of sites where more detailed studies could be undertaken are shown in fig. 1. Sediment drill cores could be taken from a lagoon 6 km south of Vohemar (site 1 in fig. 1) and from inner reef sedimentary deposits of the intertidal zone immediately north of the former necropolis (*e.g.* site 2 in fig. 1). These sites may have preserved records of overwash events due to, for example, storm surges and wave run-up. The thickness of these deposits, their lateral extent and grain size may show the relative magnitude of these events. Drilling campaigns need to be accompanied by detailed mapping of geomorphic forms and processes around the

drilling sites. Multi-proxy studies of the sediment cores recovered would need to include pollen and microcharcoal analyses, multi-element geochemical analyses and magnetic susceptibility studies. In addition to lagoonal and intertidal sediments, layered coral skeletons from reefs near Vohemar (*e.g.* site 3 in fig. 1) could also be used for palaeo-environmental reconstructions and to determine possible environmental contamination as a result of anthropogenic impact. Other sites that could provide insights in the palaeo-environmental history of the area are the wetlands (site 4 in fig. 1) 1 km southwest of the necropolis and recent dunes about 7 km south of Vohemar (site 5 in fig. 1).

24 Coastal sediments represent complex features of past environmental change. For deciphering the history of past changes, triggered by both natural processes as well as human impact, it is necessary to rely on physical dating as outlined in the present article. While radiocarbon and uranium series methods can provide reliable time frames, OSL offers the highest flexibility with regard to dating range (from several years to a few hundred thousand years). Most importantly, OSL can be applied to almost any kind of sediment, which offers a huge potential for dating natural environmental variability as well as the presence and impact of humans in coastal areas. A comparison of archaeological and dated palaeoenvironmental records may elucidate the reciprocal relationships between ecosystem dynamics, climatic changes and human settlement in the Vohemar region and may shed light on the rise and fall of the Rasikajy civilisation.

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Pour citer cet article

Référence électronique

Frank Preusser et Guido Schreurs, « Dating sediments in coastal areas and potential applications for constraining the palaeo-environmental context of an archaeological site at Vohemar », *Études océan*

Indien [En ligne], 46-47 | 2011, mis en ligne le 03 mars 2013, consulté le 15 juillet 2016. URL : http://oceanindien.revues.org/1344 ; DOI : 10.4000/oceanindien.1344

Référence papier

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Droits d'auteur

Résumés

We present an overview on different environmental zones within coastal areas and summarise the physical basis behind the three most important methods that are available to date Holocene coastal sediments. Besides radiocarbon and uranium series dating, Optically Stimulated Luminescence (OSL) has increasingly been applied for dating in coastal settings over the past decade. This is illustrated by a number of case studies showing that OSL can be applied to sediments from almost any kind of coastal environment, covering a potential dating range from some years up to several hundred thousand years. OSL dating may hence be the method of choice for deciphering natural environmental change along coasts as well as the presence and the impact of human occupation in such areas. In addition, we briefly show how and where these dating methods could be applied to constrain the palaeo-environmental context of an archaeological site at Vohemar in north-eastern Madagascar.

Nous présentons un aperçu sur les différentes zones environnementales dans les secteurs côtiers et proposons de résumer les bases physiques des trois méthodes les plus importantes disponibles à ce jour pour dater les sédiments côtiers de l'holocène. Outre le radiocarbone et la datation série de l'uranium, la luminescence stimulée optiquement (OSL) a été la plus appliquée pour la datation en milieu côtier durant la dernière décennie. Ceci est illustré par un certain nombre d'études de cas montrant que l'OSL peut être appliquée à des sédiments à partir de presque n'importe quel type de milieu côtier, couvrant une datation potentielle de quelques années jusqu'à plusieurs centaines de milliers d'années. La datation par OSL peut donc être une méthode de choix pour décrypter les changements environnementaux naturels le long des côtes ainsi que la présence et l'impact de l'occupation humaine dans ces zones. De plus, nous avons brièvement montré comment et où ces méthodes de datation pourraient être appliquées pour circonscrire le contexte paléo-environnemental d'un site archéologique comme Vohémar, dans le nord-est de Madagascar.

Entrées d'index

Mots-clés : luminescence stimulée optiquement, datation au radiocarbone, datation série uranium, récifs coralliens, zone de marée, dépôts littoraux, étendues côtières, paléo-environnement, Rasikajy
Keywords : Optically Stimulated Luminescence, Radiocarbon Dating, Uranium Series Dating, Coral Reefs, Tidal Zone, Shoreline Deposits, Coastal Flats, Palaeo-environment, Vohemar, Rasikajy
Noms de lieux : Vohémar (Madagascar)

Domaines : archéologie

Note de l'auteur

Comments from Tony Reimann on an earlier version are greatly appreciated.